AIR FLOW MEASUREMENT ACCURACY

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BACKGROUND

Accurate measurement of air flow in heating, ventilating and air conditioning (HVAC) systems can be difficult if not impossible in certain situations. Some of the challenges include space limitations, too low an air velocity, non-uniformity of the velocity profile, and sensor cost.

Industry standards suggest the need to traverse or measure air flow at multiple points across a duct cross-section to obtain an accurate measure of the average velocity. Traverses are usually performed as part of air system balancing with an accuracy within 5-10% of the actual flow. In some cases the accuracy may be worse when the traverse is performed in less than ideal conditions.

The traverse concept is also used by airflow sensor manufacturers to measure average airflow in monitoring or control applications. These flow sensors consist of a number of single-point sensors arranged in a traverse-like pattern or array. The single-point measurements are averaged together to yield an output signal representative of the average duct flow.

Interestingly, a survey of commercial air flow measurement device vendors showed that they do not all adhere to the minimum point density requirements recommended by the standards organizations. This paper presents laboratory test data in support of a lesser point density requirement than that suggested by the standards organizations.

INTRODUCTION

The U.S. Army Construction Engineering Research Laboratories (USACERL) full-scale HVAC test facility was used to investigate duct air flow measurement in a straight duct section at various duct diameters (distances) downstream of a 90^{o} elbow and at different airflow rates. The results were analyzed to characterize the flow profiles and to compare the traverse data to a three-point air flow measurement. In addition, the potential for using a single-point measurement to obtain an accurate measure of airflow was investigated.

A COMPARISON OF TRAVERSE STANDARDS AND METHODS

Tables 1 and 2 compare air flow traverse recommendations of ASHRAE[1], SMACNA[2] and AABC[3] standards organizations to each other and to the sensor point density recommendations of airflow arrays manufactured by several different vendors.

Tables 1 and 2 show the flow measurement point densities for different square duct areas and includes breakpoints where the point density changes. Although the standards organizations base the number of traverse points on the side dimensions of the duct, Table 1 was formulated based on duct area to facilitate comparison with the vendor supplied data in Table 2. The duct area breakpoints in Tables 1 and 2 are based on information supplied by vendor A because their point densities agreed most closely with the standards organizations. Tables 1 and 2 also show the point density for the specific duct (6.1 ft^2) used to take data for this study.

As shown in Table 1, each of the standards organizations provide guidance based on either the Equal Area or Log-Tchebycheff methods.

The Equal Area method requires the duct to be segmented into equal sized areas, ordinarily with no more than 6 inches between the center point of each area. A flow measurement is made at the center point of each area afterwhich all the measurements are averaged. This method would work very well for a flat velocity profile.

The Log-Tchebycheff method takes into account the rounded (bullet) shape of the velocity profile as the velocity falls off toward the edges of the duct. Spacing of the traverse points is designed to measure areas of equal volume flow therefore the distance from one traverse point to the next is not constant.

ASHRAE recommends the Log-Tchebycheff method, AABC recommends the Equal Area method, while SMACNA supports either but appears to indicate no preference. Although ASHRAE recommends the Log-Tchebycheff method, for small ducts with sides less than 18 inches, it suggests using the Equal Area method.

ASHRAE and AABC are fairly consistent with each other in their recommendation that flow measurements be made 7½ duct diameters downstream of any flow disturbance. They vary slightly in that they recommend 3 and 2½ duct diameters, respectively, upstream from any disturbance. SMACNA recommends flow measurement 6 to 10 straight duct diameters downstream of flow disturbances, but provides no guidance on upstream distance.

TABLE 1. AIR FLOW TRAVERSE POINT DENSITY RECOMMENDATIONS.
(A Comparison of Different Industry Standards.)

<table>
<tr><th rowspan="2">Duct Area</th><th colspan="2">ASHRAE[1]</th><th colspan="2">SMACNA[2]</th><th colspan="2">AABC[3]</th></tr>
<tr><th>EQUAL AREA</th><th>LOG-TCHEBYCHEFF</th><th>EQUAL AREA</th><th>LOG-TCHEBYCHEFF</th><th>EQUAL AREA</th><th>LOG-TCHEBYCHEFF</th></tr>
<tr><td>< 2.25 ft^2</td><td>4-9 Points
Not more than 6" apart</td><td>Use Equal Area method</td><td>15 Points
Not more than 6" apart</td><td>25-47 Points
No specific guidance for different size ducts</td><td>16 Points
Not more than 6" apart</td><td>25 Points</td></tr>
<tr><td>< 4 ft^2</td><td>Use Log-Tchebycheff method</td><td>25-49 Points
No specific guidance for different size ducts except as noted below</td><td>15-16 Points
Not more than 6" apart</td><td rowspan="5">SAME AS ABOVE</td><td>16 Points
Not more than 6" apart</td><td>25 Points</td></tr>
<tr><td>4-16 ft^2</td><td rowspan="4">SAME AS ABOVE</td><td>SAME AS ABOVE</td><td>15-64 Points
Not more than 6" apart</td><td>16-64 Points
Not more than 6" apart</td><td>25-49 Points</td></tr>
<tr><td>6.1 ft^2 **</td><td>SAME AS ABOVE</td><td>25 Points</td><td>28 Points</td><td>35 Points</td></tr>
<tr><td>16-32 ft^2</td><td>For area > 21.8 ft^2
Use points not more than 8" apart
(Equal area?)</td><td>64 Points
Not more than 64 points necessary</td><td>64 Points
Not more than 64 points necessary</td><td>25-49 Points</td></tr>
<tr><td>>32 ft^2</td><td>Use points not more than 8" apart
(Equal area?)</td><td>64 Points
Not more than 64 points necessary</td><td>64 Points
Not more than 64 points necessary</td><td>24-49 Points</td></tr>
</table>

** Example application for which test data was taken.

TABLE 2. AIR FLOW SENSOR POINT DENSITY RECOMMENDATIONS.
(A Comparison of Different Vendors).

Duct Area	VENDOR A (PITOT)	VENDOR B (THERMAL)	VENDOR C (THERMAL)	VENDOR D (THERMAL)
< 2.25 ft^2	1-9 Points	1-9 Points	1 or 2 Points	
	1 point for every 16 in^2 of station area.	4 Points/ft^2		
< 4 ft^2	1-16 Points	1-16 Points	1 or 2 Points	
	SAME AS ABOVE	SAME AS ABOVE		
4-16 ft^2	16-64 Points	16 Points	2-4 Points	
	1 point for every 36 in^2 of station area; max of 120 pts	16 Points per unit		
6 ft^2 **	25 Points	16 Points	2 Points	1 Point
16-32 ft^2	64-100 Points	16-32 Points	4-8 Points	
	SAME AS ABOVE	1 Point/ft^2		
>32 ft^2	100-120 Points	8+ Points	8+ Points	
	SAME AS ABOVE	1 Point/4 ft^2		

** Example application for which test data was taken.

In Table 2, Vendor A's recommended point densities are consistent with ASHRAE and SMACNA, but Vendors B, C and D vary significantly from ASHRAE and SMACNA.

Vendors A and B provide point density guidelines in their product literature. Vendor C provided general guidelines over the phone. Vendor D deals primarily in gas flow measurement and would only provide a recommended point density for the test application used in this study.

In each case the guidelines from the vendors include the requirement that the flow measurement be accomplished at least 5 duct diameters downstream of any obstruction. Vendor A literature also provides guidelines for flow measurement at 1 to 2 duct diameters downstream and/or upstream of various obstructions when a honeycomb type airflow straightener is used.

Vendor A is the only vendor surveyed who manufacturers a pitot tube type airflow measurement array. Vendor A manufactures an electronic flow sensor, but it is only available in a single-point configuration. Vendors B, C and D manufacture only electronic type sensor arrays.

TEST APPARATUS AND APPROACH

Air flow traverses were performed at four different locations in a long straight section of ductwork in the USACERL HVAC test facility. Only one location, 20 feet downstream of an elbow and 8 feet upstream of a split, met ASHRAE, SMACNA, and AABC recommendations.

Each traverse consisted of 35 point measurements, as shown in Figure 2A, using the Log-Tchebycheff method consistent with or exceeding industry standards for the size of the duct (22" by 40"). Each traverse was performed twice at three different airflow rates.

A hot wire anemometer, with calibration traceable to NIST standards, was used to make the traverse flow measurements. For a single measurement, the voltage output from the anemometer was fed into a data acquisition unit that took 100 readings over a ten second interval then averaged these readings to yield the single point measurement. Velocity readings were adjusted from standard calibration conditions to actual test conditions based on barometric pressure and duct temperature.

Measurements were also taken with a commercial grade air flow probe. The probe location is shown in Figure 1. The probe contained three point sensors that traversed the duct along its largest axis (40" width) as shown in Figure 2B. The probes flow sensors are located 7 inches from each side of the duct (17.5% of the width) and one in the middle. The probe averaged the three velocity readings and provided a single output signal which was measured using an industrial grade controller.

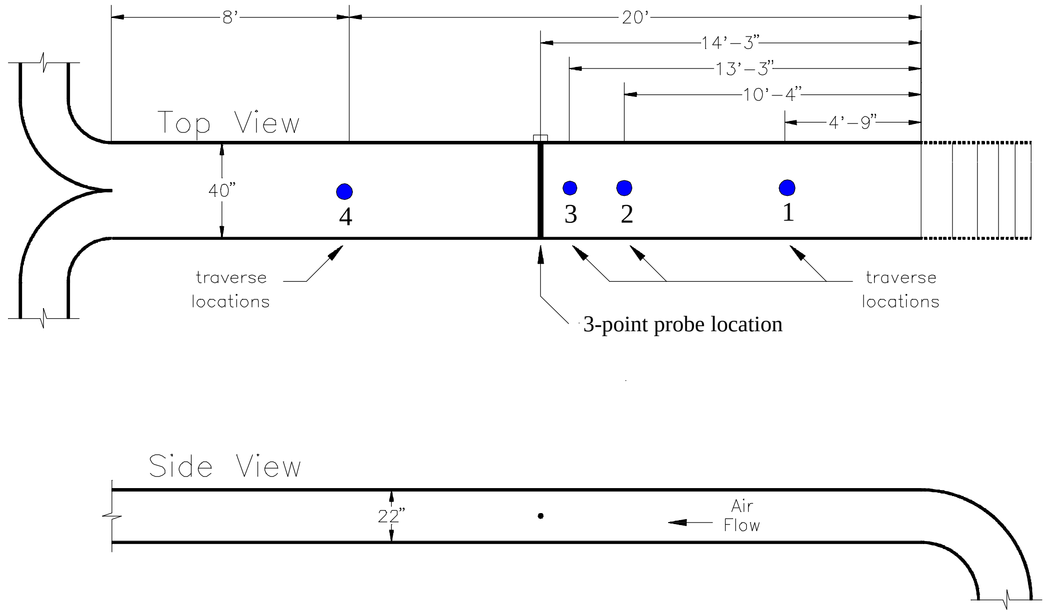

Figure 1. Traverse and Airflow Probe Locations in HVAC Test Facility Duct Section.

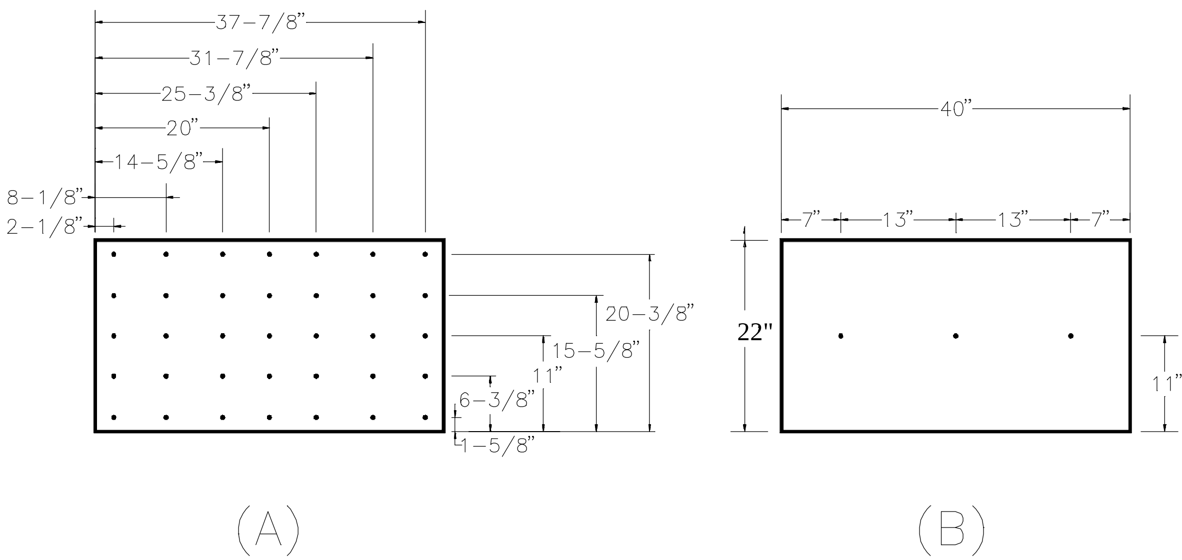

Figure 2. Point locations for: A) 35-point Traverse, B) 3-point Probe

To investigate the accuracy of a 3-point measurement, 3-point traverses were performed using the hot wire anemometer. The 3-point traverse measurements were taken one foot upstream and directly in front of the sensors on the commercial 3-point flow probe.

The HVAC test facility contains no air flow straightening devices although there is a cooling coil (not shown in Figure 1) located approximately 15 feet upstream and below the elbow.

RESULTS

In summary, the flow data for the particular rectangular straight duct section indicates that:

- There is little to no difference in accuracy between a 35-point traverse performed 2 duct diameters downstream and one performed 7.5 duct diameters downstream of the elbow
- The commercial grade 3-point averaging air flow probe provided an accuracy comparable to a 35-point traverse measurement
- A single-point found to be representative of the average duct flow, as identified via a full traverse, will remain representative of the average flow across a wide range of flow rates,
- The flow profile, as viewed from the side of the duct tends to maintain itself, across a wide range of flow rates, such that a single point along the profile, representative of the average duct flow rate is always at the same vertical point in the duct.

Table 4 shows the 35-point traverse data taken twice at three different flow rates at each of the four locations. The average flow was nearly identical at each of the four traverse locations shown in Figure 1. This was true at each of the three flow rates (low, medium and high).

Table 4 compares each traverse flow rate, as a percent difference, to the reference flow at 7½ duct diameters (20 ft) downstream of the elbow. The results suggest that accurate flow readings may be taken as close as 2 duct diameters beyond the elbow (5'4" in this study). This is in contrast to industry standards which suggest that flow measurements be made 7½ duct diameters downstream of any flow disturbance.

The reference 35-point traverse (at 7½ duct diameters downstream of the elbow) is estimated to have a root mean square (RMS) accuracy of ± 3.7%. The RMS takes into account: The 35-point traverse method (3.0%), the certified anemometer calibration accuracy (0.25%), the anemometer rated accuracy (2.20%), and the data acquisition unit accuracy (0.02%).

Table 4. 35-Point traverse accuracy at different distances from elbow.

Test no.	Flow Rate	Loc (ft)	Trav. (fpm)	Percent Difference
1	Low	20	316	Reference flow
2		13	311	-1.6%
3		10	316	0.0%
4		5	313	-0.9%
5	"	20	305	Reference flow
6		13	310	1.6%
7		10	312	2.3%
8		5	314	3.0%
9	High	20	937	Reference flow
10		13	943	0.6%
11		10	951	1.5%
12		5	944	0.7%
13	"	20	936	Reference flow
14		13	942	0.6%
15		10	947	1.2%
16				No data
17	Med	20	598	Reference flow
18		13	604	1.0%
19		10	600	0.3%
20		5	598	0.0%
21	"	20	594	Reference flow
22		13	595	0.2%
23		10	602	1.3%
24		5	597	0.5%

Table 5 shows the results of a 3-point traverse (taken 1 foot upstream of the commercial 3-point flow probe). The traverse was performed twice at the medium air flow rate and compared to a 35-point traverse. In both cases the 3-point traverse was within 1.0% of the 35-point traverse. This suggests that, for the duct section studied, a 3-point measurement can provide accuracy comparable to a 35-point measurement.

Table 5. Comparison of a 3-point traverse to a 35-point traverse.

Test No.	Flow Cond.	Loc (ft)	3-Pt Trav (fpm)	35-pt Trav (fpm)	Percent difference

18	Med	13	598	604	1.0%
22	Med	13	592	595	0.5%

Table 6 compares the 3-point probe to a 35-point traverse. The 3-point probe is not very accurate at low flow rate, but is quite accurate at high flow rate. Since the device appears to be linear (as indicated in Figure 3), the inaccuracy might be attributed to calibration error of the instrument (as opposed to measurement error due to only three flow points being sensed). While this commercial grade probe demonstrated a degree of calibration inaccuracy, it and the 3-point traverse data suggest that a 3-point measurement can provide good measurement of the duct average flow.

Table 6. Comparison of the 3-point probe to a 35-Point traverse.

Flow Cond	Duct Loc. (ft)	3-Pt Probe (fpm)	35-Pt Trav. (fpm)	Percent Difference
Average Low	13	267	311	-14.1%
Average Med	13	565	599	-5.8%
Average High	13	944	943	0.2%

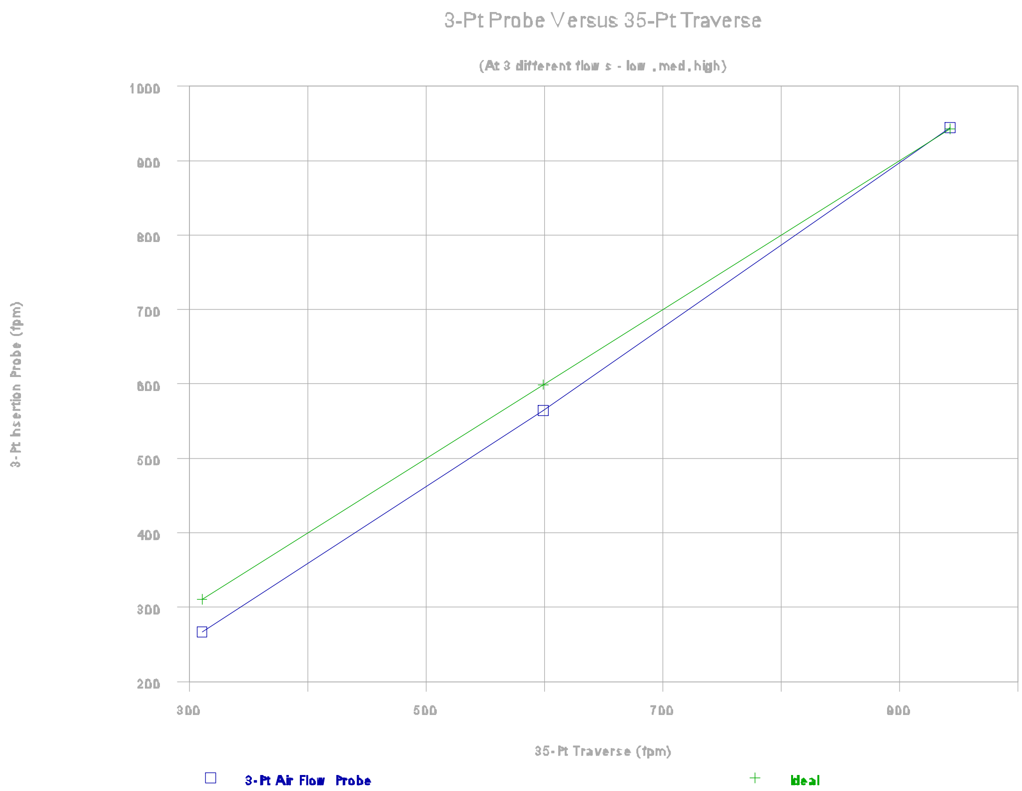

Figure 3. Accuracy of a commercial 3-Point probe as compared to a full 35-point traverse of the rectangular 22"x40" duct.

Table 7 shows a simulated 3-point measurement. The simulation consists of a linear interpolation between adjacent points from the 35-point traverse data corresponding to the locations of the three sensors on the 3-point probe. This approach was used to compare a 3-point measurement to a 35-point measurement at all duct locations. While this simulation approach cannot be considered definitive because of the turbulent nature of the duct flow, it does provide a basis for comparison.

At all traverse locations the simulated 3-point measurement compares well with the 35-point traverse. The overall average error (for 23 tests) is 2.0% with the 3-point simulation resulting in a higher flow than the 35-point traverse in all cases. The worst single-case error is 4.0%. The worst case average error is 2.7% at the 20 foot location. The average error at the 5 foot location is 2.5%.

Table 7. Comparison of the simulated 3-point measurement to the 35-point traverse.

Test No.	Air Flow Cond	Duct Loc. (ft)	35-Pt Trav. (fpm)	3-Pt Simul. (fpm)	Percent Difference
1	Low	20	316	326	3.0%
2	Low	13	311	317	1.9%
3	Low	10	316	322	1.9%
4	Low	5	313	322	2.8%
5	Low	20	305	316	3.4%
6	Low	13	310	316	1.8%
7	Low	10	312	318	1.7%
8	Low	5	314	326	4.0%
9	High	20	937	366	1.6%
10	High	13	943	963	2.1%
11	High	10	951	959	0.8%
12	High	5	944	960	1.7%
13	High	20	936	959	2.5%
14	High	13	942	948	0.6%
15	High	10	947	949	0.2%
16	No Data				
17	Med	20	598	616	3.0%
18	Med	13	604	608	0.8%
19	Med	10	600	606	1.0%
20	Med	5	598	606	1.3%
21	Med	20	594	610	2.7%
22	Med	13	595	607	2.0%
23	Med	10	602	611	1.5%

24	Med	5	597	613	2.6%

The feasibility of an accurate measurement using a three-point probe may at least in part be attributed to the fact that at all flow rates studied the airflow was turbulent as indicated by the Reynolds number (Re):

Re (at 312 fpm) = 83,000
Re (at 598 fpm) = 159,000
Re (at 942 fpm) = 250,000

Turbulent flow is generally present when the Reynolds number is above 2300 although the flow may remain laminar (under ideal conditions) up to a Reynolds number of 40,000. Clearly the flows studied here are turbulent. Unlike laminar flow, turbulent flow does not develop a well rounded "bullet" shape profile. As expected the observed velocity profiles, while bullet shaped, were relatively flat.

Table 8 provides some insight into the relative flatness of the velocity profiles by comparing the standard deviation of the 35 measurements to the averaged duct flow. The "Far Down Stream" location is 7.5 duct diameters beyond the 90° elbow and the "Close to Elbow" location is 2 duct diameters beyond the 90° elbow. As shown in Table 8, at the "Far Down Stream" location the standard deviation ranges from about 6% to 8% of the average duct flow for the three flow rates studied. This indicates a good probability of any individual point measurement being within the average flow range. A larger standard deviation indicates a less flat profile.

Table 8. Standard deviation of the 35 traverse points.

Avg. Flow (cfm)	Far Down Stream (20 foot location)		Close to Elbow (5 foot location)	
	Std.Dev.	% of Avg.	Std.Dev.	% of Avg.
312	26	8.3%	40	12.8%
598	45	7.5%	76	12.7%
942	56	5.9%	116	12.3%

As the flow rate changes, the profile does not change appreciably as is illustrated in Figures 4 through 8. Table 8, though, indicates that as the flow rate increases the profile flattens slightly, more so further down stream than close to the elbow. This is evidenced by the decrease in the percent change of the standard deviation with respect to the average flow.

The traverse data indicates, for the duct section studied, that a single traverse point, selected as representative of the average flow, remains representative at any air flow rate. Substantive data in support of this is not presented here as it was more of a casual observation resulting from study of the 24 sets of traverse data. This conclusion is supported though by Figures 5 through 9 which show side and top view profiles at each flow rate for several of the traverse locations. It is evident that the average flow location remains relatively constant regardless of the flow rate.

CONCLUSIONS

The results and conclusions are based on a single, rectangular shaped, straight duct section. The results may not be be transferrable to other duct sections or configurations. Additional sections would need to be studied to warrant changing U.S. Army Corps of Engineers air flow measurement criteria. For the rectangular straight duct section studied, the flow data indicated that:

- An air flow straightener is not required to get an accurate air flow measurement
- Air flow instrumentation need not be located more than 2 duct diameters downstream of an elbow that does not contain turning vanes
- A 3-point averaging air flow measurement instrument can provide accuracy comparable to a 35-point traverse measurement and to a measurement based on ASHRAE or SMACNA guidelines.
- The flow profile, as viewed from the side of the duct tends to maintain itself, across a wide range of flows, such that a single point along the profile, representative of the average duct flow is always at the same vertical point in the duct
- A single-point found to be representative of the average flow, as identified via a full traverse, will remain representative of the average flow across a wide range of flows

ACKNOWLEDGEMENTS

This work was performed for Headquarters, U.S. Army Corps of Engineers (HQUSACE) under AT45 program project “Advanced HVAC System Technologies” work unit X47. Most of the data was collected by Alec Gibson a former research assistant. Bruce Keaton, another former research assistant, also contributed to the development of this paper.

REFERENCES

1. ASHRAE Fundamentals Handbook, 1993, and ANSI/ASHRAE Standard 111-1989.
2. SMACNA HVAC SYSTEMS: Testing, Adjusting and Balancing, 2nd Ed., 1993.
3. Associated Air Balance Council, 5th Ed., 1989

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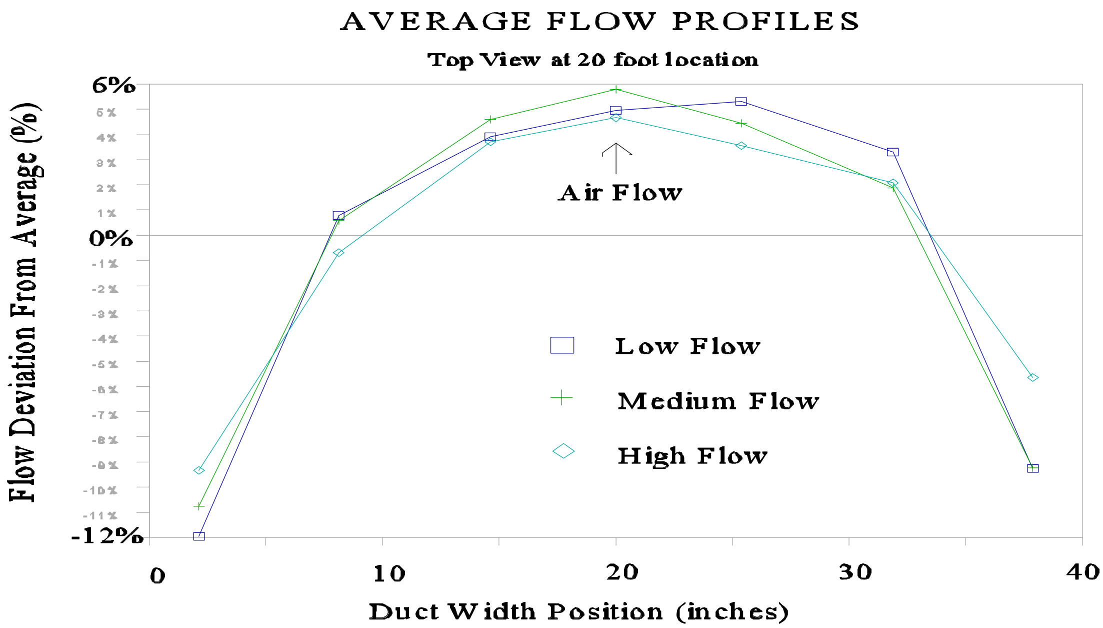

Figure 4. Average flow profile as viewed from the top of the duct at the 20 foot location at 3 different air flow rates.

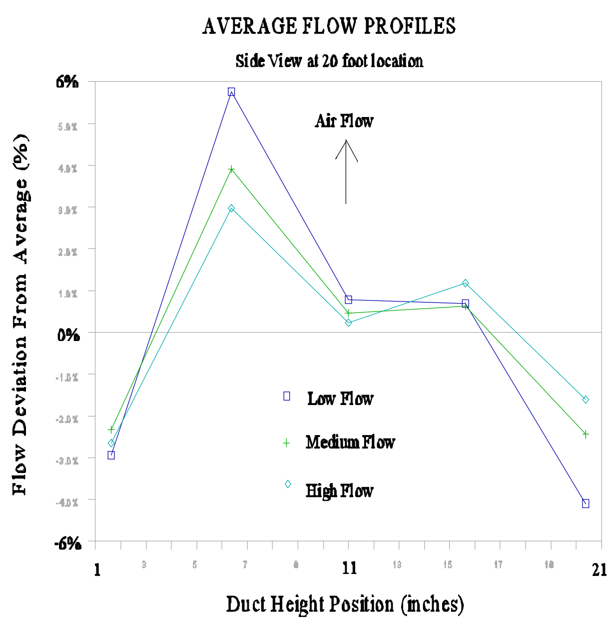

Figure 5. Average flow profile as viewed from the side of the duct at the 20 foot location at 3 different flows (rotate graph 90° counter-clockwise to view exact orientation).

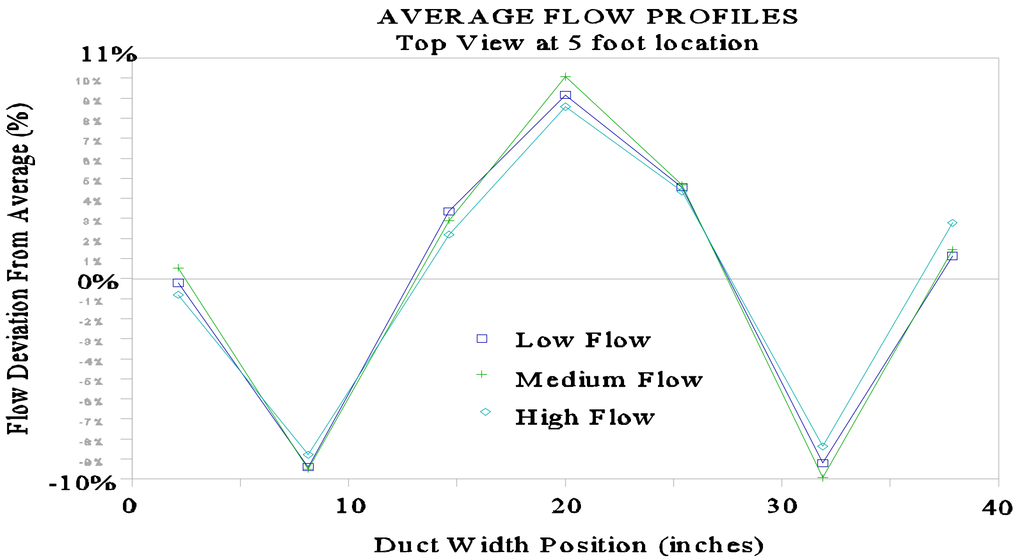

Figure 6. Average flow profile as viewed from the top of the duct at the 5 foot location at 3 different flow rates.

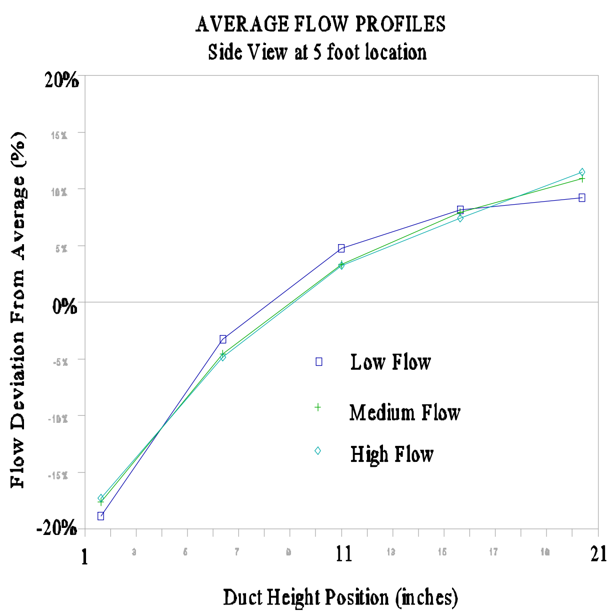

Figure 7. Average flow profile at the 5 foot location at three different flow rates, as viewed from the side of the duct (rotate graph 90° counter-clockwise to view exact orientation).

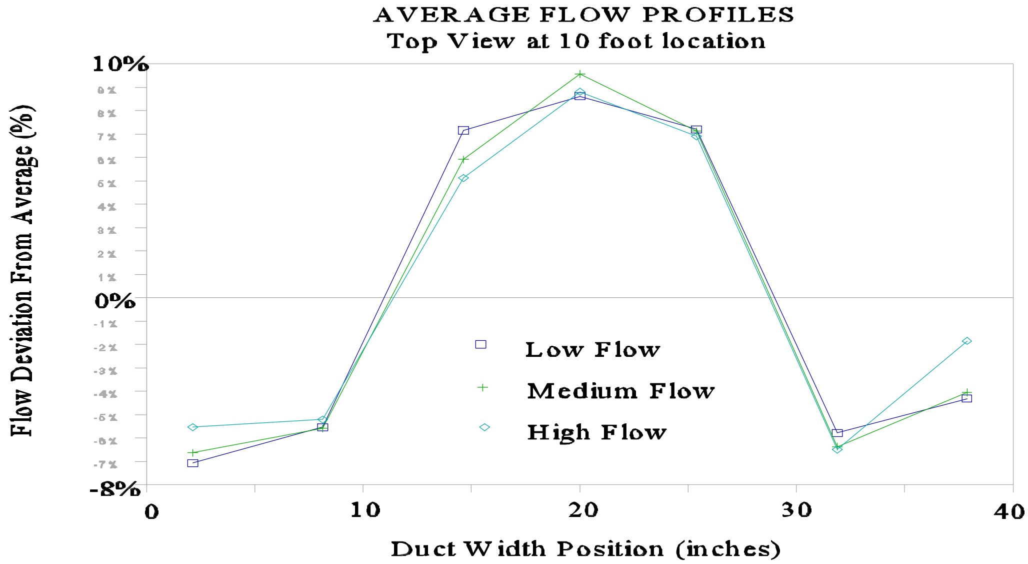

Figure 8. Average flow profile, as viewed from the top of the duct at the 10 foot location at 3 different flow rates.

30 November 1997

Joe,

I know some of the figures are hard to read. Time permitting, I will try to make them clearer. If you think I MUST make them clearer, let me know and I will.

Also, anything that is underlined should be in italics, but my printed will not italicize. I will fix this prior to publication.

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Figure 2. Duct height is 22" not 20" (ACAD file: AIR-RPT2.DWG)
SMACNA and ASHRAE - standard, recommendation, or guideline?

Get reference document info for SMACNA and ASHRAE

metric m/ft.

For each traverse, the average air flow was determined in addition to the standard deviation, maximum and minimum flows. For each traverse point, its deviation from the average flow was determined and tabulated to characterize the nature of the flow through the duct as it traveled the length of the duct section.

The data showed that the 35 point traverse measurement was accurate at each location tested.

Add percentages to table 3.   3-pt vs 35-pt traverse %

equiv diameter of 22"x40" duct = 32.1"

Other observations:

- Two, 5-10 year old instruments no good
- Repeatability of traverses -- how good?

Show in drawing:

- distance of each traverse (dimensions)
- duct dimensions
- top and side views
- location of probe
- cross section of duct with traverse points and dimensions
  - include probe point locations in same drawing as "X's"
- separate drawing of probe with sensor pt dimensions
  - (to scale with duct cross section)

Symphony files: CD-ANAL.WR1

Vendor A = Air monitor
Vendor B = Ebtron
Vendor C = Kurz
Vendor D = Sierra

Table 3 summarizes the traverse locations in terms of distance and duct diameter (at an equivalent duct diameter of 32 inches, based on the 22x40 inch duct). Table 3 shows similar data for a commercial probe located in the duct section and shows ASHRAE and SMACNA recommended distances for measuring airflow.

	Downstream Distance from Obstruction		Upstream Distance from Obstruction	
	m (ft.)	Duct Diam.	m (ft.)	Duct Diam.
Traverse Location 1	(4'9")	1.8	exceeds min.	exceeds min.
Traverse Location 2	(10'4")	3.9	exceeds min.	exceeds min.
Traverse Location 3	(13'4")	5.0	exceeds min.	exceeds min.
Traverse Location 4	(20')	7.5	(8')	3
Commercial Probe	(14'3")	5.3	exceeds min.	exceeds min.
ASHRAE minimum	(20')	7.5	(8')	3
SMACNA minimum	(20')	7.5	(6'8")	2.5

Table 3. Distances and equivalent duct diameters for airflow measurements.

Re = V x L / *v*

> **V = Air velocity, ft/sec**
> **L = Equivalent diameter of rectangular duct = 2.675 ft**
> ***v* = Kinematic viscosity = 0.000168 ft^2/sec**

COLD DECK TRAVERSE DATA
(8 Aug 94)

Test no.	Flow Cond	Loc (ft)	Trav (fpm)	Probe (fpm)	P+/-	3Pt-Sim (fpm)	3Pt-Act (fpm)
1	Low	20	316	267	20	326	
2	Low	13	311	267	20	317	
3	Low	10	316	267	20	322	
4	Low	5	313	267	20	322	
5	Low	20	322	267	20	316	
6	Low	13	310	267	20	316	
7	Low	10	312	267	20	318	
8	Low	5	314	267	20	326	
9	High	20	937	944	50	366	
10	High	13	943	944	50	963	
11	High	10	951	944	50	959	
12	High	5	944	944	50	960	
13	High	20	936	944	50	959	
14	High	13	942	944	50	948	
15	High	10	947	944	50	949	
17	Med	20	598	565	50	616	611
18	Med	13	604	565	50	608	598
19	Med	10	600	565	50	606	596
20	Med	5	598	565	50	606	601
21	Med	20	594	565	50	610	599
22	Med	13	595	565	50	607	592
23	Med	10	602	565	50	611	600
24	Med	5	597	565	50	613	601

Test no.	Flow Cond	Loc (ft)	Trav (fpm)	Probe (fpm)	P+/-	3Pt-Sim (fpm)	3Pt-Act (fpm)
2	Low	13	311	267	20		
6	Low	13	310	267	20		
18	Med	13	604	565	50	608	598
22	Med	13	595	565	50	607	592
10	High	13	943	944	50		
14	High	13	942	944	50		
Avg	Low	13	311	267	20	-14.1%	
Avg	Med	13	599	565	20	-5.8%	
Avg	high	13	943	944	20	0.2%	

								sim-trav
4	Low	5	313	267	20	322		2.9%
8	Low	5	314	267	20	326		3.8%
20	Med	5	598	565	50	606	601	1.3%
24	Med	5	597	565	50	613	601	2.7%
12	High	5	944	944	50	960		1.7%